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Project Title

Beneficial Reuse of Landfilled Fly Ash in Transportation Infrastructure

University

Colorado State University
University of Wyoming

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Research Needs

State DOTs have been utilizing fly ash as a pozzolan in the concrete transportation infrastructure for decades. According to a recent survey by the American Coal Ash Association (ACAA), approximately 38 million tons of fly ash were produced in 2017, and about 14 million tons of which were used in concrete. The rest of 14 million tons of fly ash were disposed of in landfills. The ACAA estimates that the gap between demand and supply of concrete-grade fly ash is about 25% nationally. Shortages are being driven by the retirement and capacity reductions of coal-fired power plants and the move toward natural gas and renewable energy sources. It is anticipated that future shortages in fly ash will be more significant in the near future. As a result, the concrete industry needs to identify the availability of fly ash in various landfills/storage facilities across the country. Such information will be useful in identifying if fly ash supplies will meet future demands. In addition, there is a need to identify alternatives for fly ash since eventually, the production of fly ash will diminish in the future.

One of the existing challenges facing the reuse of landfilled fly ash (LFA) is the presence of excessive sulfur, free lime, and unburned carbon content in the ash, making it unsuitable as a pozzolan in concrete. ASTM C618-19 [1] and AASHTO M 295-21 [2], which are the two current specifications used in the US to determine the suitability of fly ash as a source of supplementary cementitious materials in concrete, have set strict prescriptive limits on the physicochemical properties of the ash, disregarding the inherent variability in various sources of fly ash and the need for identifying a suitable alternative to fly ash. Given the growing concerns regarding the shortage of fly ash in some regions, adhering to these strict limits rules out the possibility of using LFA even though they may show adequate performance in service. This project surveys the properties of LFAes in Colorado and Wyoming and evaluates the feasibility of beneficiating these ashes to meet ASTM C618-19 [1] and AASHTO M 295-21[2] requirements.

Research Objectives

In this study, researchers from Colorado State University and the University of Wyoming will work jointly with the concrete industry partners in the region to understand the role that LFA plays in controlling concrete properties in the fresh and hardened state. The overarching goal of this study is to determine if LFA that may not meet the prescriptive limits set forth in ASTM C618 [1] and AASHTO M295 [2] can show adequate performance in service and whether a new classification can be introduced based on their inherent heterogeneity in physicochemical properties and performance data. Given the current growing scarcity of high-quality fly ash, it is also essential to investigate if the beneficiation of LFA is economically justified. Thus, the four scientific questions that we will address in this project are:

1. What is the degree of variability of LFA in Colorado and Wyoming?
2. How do thermal treatment and mechanical grinding improve the properties of LFA?
3. How does the physiochemical variability of the ash create issues for concrete and contribute to its performance?
4. What extent of deviations in the physicochemical properties of LFA from ASTM C618 [1] and AASHTO M295 [2] limits can still exhibit acceptable performance in service?

Research Methods

We will use seven tasks to address the four scientific questions posed in this project and discussed above.

Task 1- Literature review (UW and CSU)

Literature review will be conducted to investigate the previous and current research on the LFAs.

Task 2 – A comprehensive survey of LFAs in Colorado and Wyoming (Lead: UW)

In this task, we will perform a comprehensive survey to investigate the following areas:

- Historic and contemporary use of LFA materials
- Current demand of LFA in Colorado and Wyoming

- Current and future availability of LFA in Colorado and Wyoming
- LFA storage capacity in Colorado and Wyoming
- National and State Regulation Governing Reuse the LFA
- Beneficiation of LFA for use in concrete
- Economics of Beneficiation
- Site-specific considerations for power plants in Colorado and Wyoming
- Technologies for LFA beneficial use in concrete

Task 3 - Design of Experiment (Lead: UW)

A detailed LFAs sampling plan will be created in this task.

1. The sampling location will be determined based on the LFA availability, transportation, permits and regulations, and site-specific considerations for power plants.
2. Landfill boundaries will be determined using photogrammetry provided by unmanned aerial vehicle (UAV) or by using remote sensing technology. Based on the historical data and the pattern in which the fly ash was filled, the landfill will be divided into various strata.
3. The FLA sampling log will be created to document important information, such as the landfilling operations dates, the pattern in which the landfill was filled, changes in the power production process, source of coal and coal rank, etc.
4. Quality control sampling strategy will be developed to ensure the fly ash with consistent quality and reliability is collected.

Task 4- Sampling LFAs in Colorado and Wyoming (Lead: UW)

This task aims to determine the extent of variability in the properties of LFA samples taken from two landfills in Wyoming and Colorado. Samples will be taken using a stratified random sampling approach outlined in ASTM D5956-15 [3]. In this project, we only consider taking samples from the topmost stratum manually. For this purpose, the landfill is divided into nine blocks using a 3×3 grid. Three blocks will be chosen randomly, and a borehole is made at the center of each block. After determining the depth of the topmost stratum, one sample will be taken at every 1.5m depth interval. For example, if the topmost stratum is 3m deep, one sample will be taken from the depth of 0-1.5m, and another sample will be taken from the depth of 1.5-3m, totaling six samples per landfill. The borings should be large enough to provide a minimum of 20kg sample. Samples will be stored in sealed containers and shipped to CSU for testing.

Task 5- Physiochemical characterization of as-received LFA (Lead: CSU)

The recovered fly ash will be tested for the moisture content first and then air-dried and sieved through sieve #16 to remove large particles. The following characterization techniques will be performed to determine the variability within and between the selected landfills.

- *Moisture content:* The moisture content of the original ashes will be determined following ASTM C311-18. In this test, a weighted sample of as received ash is dried in an oven at 110 ± 5 ℃ to a constant mass, and the moisture content, which is the amount of mass loss during the drying process, is expressed in terms of percent by the mass of the as-received sample.
- *Density:* The density of the ashes will be determined using a Le Chatelier flask as specified in ASTM C188-17 [4].

- *Fineness:* The fineness of the ash will be determined following ASTM C311-18 [5] and ASTM C430-17 [6] and by wet-sieving a sample of ash on a No.325 sieve.
- *Loss on Ignition (LOI):* LOI of the ashes will be determined following ASTM C311-18 [5]. LOI represents the amount of unburned carbon content of the ash and is measured by heating a weighted moisture-free sample of ash in a furnace at 750 ± 50 ℃ to a constant mass. The LOI is the percent mass loss of the sample.
- *Strength Activity Index:* Following ASTM C311[5], the compressive strength of concrete specimens containing Portland cement and 20% of selected LFAs will be measured at 7 and 28 days and compared to a control group with only fly ash.
- *Bulk Chemistry:* The oxide analysis and bulk composition of ashes will be determined using X-ray fluorescence analysis (PANalytical Axios XRF analyzer is available at *UW*). For this purpose, fly ash will be mixed with lithium borate, fused into a glass bead, and then used in an XRF for composition.
- *Mineralogy:* The mineral and amorphous phases of the ashes will be determined using X-ray diffraction (XRD) analysis (Bruker D8 Discover DaVinci XRD analyzer is available at *CSU*). In this test, a sample of ash will be placed in a mold and then inserted into the device for qualitative and quantitative phase analysis and characterization of the ashes.
- *Morphology and particle size distribution:* Scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy will be used to determine the shape and morphology of the ashes particles (JEOL 6500 FE-SEM-EDS is available at *CSU*). The particle size distribution analysis will be performed on SEM images using ImageJ software.
- *Pozzolanic Reactivity:* In this project, the reactivity of LFAs will be determined by measuring the amount of calcium hydroxide consumption in a model system. For this purpose, LFAs will be mixed with reagent grade calcium hydroxide in a 1:3 mass ratio and 0.5 M potassium hydroxide solution using a liquid-solid ratio of 0.9 [7, 8]. The materials will be dry-mixed, followed by four minutes of manual mixing, and then stored in a sealed container at 50±1 ℃ for ten days to promote the pozzolanic reaction. After ten days, the calcium hydroxide content of the mix will be determined using thermogravimetric analysis (TA Q500 TGA/DSC is available at *CSU*).

Task 6- Beneficiating LFA (Lead: CSU)

In this task, we will investigate the influence of three levels of heat treatment on reducing the carbon content and two levels of mechanical grinding on the and reactivity of LFA. Due to time and budget constraints, only one source of LFA will be beneficiated. Table 1 presents the details of the proposed beneficiation processes in this project. For each beneficiation process, approximately 200g of LFA is placed in a high-temperature resistant tray and placed in a muffle furnace. The samples will be kept at the specified temperature for one hour and then cooled in the air. The cooled sample will be divided into two parts, one of which is ground in a ball mill for 15 minutes and another part for 30 minutes.

Table 1. Summary of the beneficiation program

Beneficiation ID	Temperature (℃)	Grinding (min)
LFA-550-15	550	15
LFA-600-15	600	15
LFA-650-15	650	15
LFA-550-30	550	30
LFA-600-30	600	30
LFA-650-30	650	30

After beneficiation, the density, LOI, fineness, water requirement, bulk chemistry, and reactivity of beneficiated LFAs will be measured again as outlined in task 1. Once all beneficiated LFAs were characterized, areas and the extent of their nonconformance with ASTM C618 will be evaluated. Based on this evaluation, the best and worst beneficiation methods will be identified and used in Task 4 for performance testing.

Task 7- Performance Testing (Lead: CSU)

In this task, the influence of LFA (non-beneficiated and beneficiated) on the properties of fresh and hardened concrete will be investigated and compared to those of concrete containing ASTM-grade fly ash. The identified best and worst beneficiation methods will be used to produce sufficient ash for concrete testing. The corresponding as-received LFA and ASTM-grade fly ash will also be used in this task as control groups.

The properties that will be investigated include slump (ASTM C143), air content (ASTM C231), setting time (ASTM C403), strength at 7, 28, and 56 days, rapid chloride permeability test (ASTM C1202), and ASR mitigation efficiency of mortar specimens (ASTM C1567), Concrete mixtures will be designed with a water-to-cementitious materials ratio (w/cm) of 0.45, using type I/II Portland cement and LFA at 20% replacement level.

Table 2. Tentative mixture design for 1 m^3 of concrete (aggregates not shown here)

Mixture ID	Cement	SCM
Control 1	80% OPC	20% ASTM-grade fly ash
Control 2	80% OPC	20% as-received LFA
C-FLA-best	80% OPC	20% best beneficiated LFA
C-FLA-worst	80% OPC	20% worst beneficiated LFA

For testing the compressive strength, nine 4”×8” concrete cylinders will be cast for each mixture (three replicates for 7, 28, and 56-day testing). One extra 4”×8” concrete cylinder will be cast for rapid chloride permeability testing as outlined in ASTM C1202. For testing the ASR mitigation efficiency of LFAs, three mortar prisms will be prepared for each mixture using moderate/highly reactive river sand.

Expected Outcomes

The results of this project will determine the range of variability in the properties of LFAs in Colorado and Wyoming and will reveal the extent of LFAs’ non-compliance with ASTM C168. In addition, the influence of two beneficiation methods on reducing the carbon content, increasing the reactivity of LFAs, and their performance in concrete mixtures will be investigated.

The proposed project will aid the concrete industry in overcoming several challenges currently faced by a wide range of stakeholders. Foremost, there is a growing concern in the construction industry regarding the unavailability of SCMs such as fly ash, which historically was relied upon to improve concrete durability. Understanding the influence of LFA on the concrete properties and the development of a performance benchmark for LFA in this project can provide long-term performance data and bring forth an economic justification for beneficiating and reusing LFA. Considering that there is inherent variability in the chemical and physical properties of LFA, in this project, we will take a methodic approach to identify the maximum limits of deviations from the required chemo-physical properties of fly ash, set forth in ASTM C618 and AASHTO M295, that can exhibit acceptable concrete performance in service. Currently, a classification for LFA is nonexistent. Therefore, it is expected that the results of this project can serve as the basis of future classifications of landfilled ash in the codes and specifications.

Relevance to Strategic Goals

This project will augment the USDOT strategic goal and high-priority area of *Environmental Sustainability* and aims at developing innovative approaches to improve the sustainability and resilience of transportation infrastructure. Historically, less than 50% of the pulverized coal combustion residuals, or coal ash, produced at power plants in the United States has been beneficially used, while the rest has been dry-landfilled or stored in ponds. Although various environmental measures are implemented to protect the environment at these landfills, this large quantity of landfilled ash can still pose significant risks to the environment and the health of communities near these disposal sites. One promising approach to reducing the negative environmental impacts of landfilled coal ash is to reuse the ash as a raw material in other industries. For example, due to the dwindling supply of high-quality fly ash caused by shutdowns of coal-fired plants and changing energy trends [9], there is a growing interest in recovering LFA for applications in the concrete industry [9, 10] . Based on current practices, it is estimated that by the year 2030, the demand for fly ash for use in concrete could exceed 35 million tons per year while the supply of high-quality fly ash would remain near or below current levels at 14 million tons [11]. Therefore, alternatives to fly ash must be evaluated to ensure the production of sustainable and durable highway concrete.

Educational Benefits

The Department of Construction Management at Colorado State University, with more than 800 undergraduate students, is one of the largest CM departments in the nation. PI Shakouri currently teaches CON-151, which is an introductory course to construction materials. The findings and materials developed in this project will be used in the class lectures to enhance students' knowledge, stretch their environmental awareness, and promote critical thinking regarding sustainable construction. In addition, to foster more hands-on learning, students can use some of the produced materials from this project in their CON-370: Asphalt and Concrete Pavement class to study the influence of LFAs on the properties of concrete and asphalt. This research will engage students at both undergraduate and graduate levels. Those hired to work on this project will be required to present their work at university research showcases, national conferences, and local construction-related chapters.

Two M.S. students will be part of the research team. Both students will work in close collaboration, but one of the students will be responsible for the experimental work at CSU, while the other student will be mainly responsible for surveying and data collection from the industry partners at UW. The project will involve one undergraduate research assistant recruited from the Honors College at the sophomore level. The student's commitment will culminate in a research showcase presentation.

We will also create educational modules and technical presentations to translate our knowledge to consultants, designers, industry groups, advocacy groups, and government agencies. We expect that our research results will lead to the development of new international standards and guidelines for fly ash classification.

Technology Transfer

A final report will be generated as a part of this research. The report will contain relevant information on materials and methods used in this project. All data will be included in the final report such that other researchers can use the data for comparison and possibly further analysis. The results of this project will be published in at least one peer-reviewed journal. Industry tech notes will also be prepared through the collaboration between the PIs and industry partners in this project.

We will propose a technical session at a future ACI Convention on the beneficial reuse of landfilled fly ash in transportation infrastructure to disseminate our results. We will also present our research findings and outcomes at relevant ACI and ASTM technical and code committee meetings. The undergraduate students will make short non-technical videos and post them on Internet-based media (e.g., YouTube and Facebook) to disseminate the findings of the project among other undergraduate students and the Internet community.

Work Plan

Task #	Task Description	Time (month) 01/2022 - 06/2023																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Literature review	■	■																
2	A comprehensive survey of LFAs in CO and WY		■	■	■														
3	Design of experiment			■	■	■													
4	Sample collection				■	■	■	■											
5	As-received LFA characterization								■	■									
6	LFA beneficiation and characterization									■	■	■							
7	Performance testing in concrete and mortar samples											■	■	■	■	■	■	■	
-	Report write-up																■	■	■

Project Cost

Total Project Costs: $88,000
MPC Funds Requested: $40,000
Matching Funds: $48,000
Source of Matching Funds: Colorado State University

References

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3. ASTM D596, *Standard Guide for Sampling Strategies for Heterogeneous Wastes*, in *ASTM International*. 2015: West Conshohocken, PA.
4. ASTM C188, *Standard Test Method for Density of Hydraulic Cement*. 2017: ASTM International West Conshohocken, Pa.
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8. Suraneni, P. and J. Weiss, *Examining the pozzolanicity of supplementary cementitious materials using isothermal calorimetry and thermogravimetric analysis.* Cement and Concrete Composites, 2017. **83**: p. 273-278.
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